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Assessment of the optimum operation conditions of a plate heat exchanger for waste heat recovery in textile industry

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ABSTRACT

Textile industry plays an important role economically in Turkey. A great amount of hot waste liquids and gases are let out in many textile processes. These waste liquids and gases have crucial energy saving potential, especially for dyeing process. It could be possible to provide energy saving by employing a waste heat recovery system (WHRS). The optimum operation conditions were assessed by integrating the first and the second law of thermodynamics for a counter flow PHE employed for a dyeing process in textile industry. The WHRS has been established by a well-known blanket manufactory located in Usak Organized Industrial Zone (UOIZ), Turkey has been evaluated. While the waste water mass flow rate varies between 8 and 12 m^3/h, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 5.55 to 13.68 kW; from 53.6% to 67.2% and from 0.996 to 0.810, respectively. Optimum waste water and cold water mass flow rate was found as 10.00 and 7.00 m^3/h, respectively. While the cold water mass flow rate varies between 5 and 9 m^3/h, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 8.05 to 10.89 kW; from %56.3% to %63.9% and from 0.868 to 0.991, respectively. While the waste water inlet temperatures vary between 52.4 and 59.5 °C, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 5.40 to 9.46 kW; from 68.7% to 61.6% and from 0.969 to 0.924, respectively at optimum mass flow rates. The present study has a great potential to serve applications of WHRS for textile application especially dyeing process. It is expected that the approach presented here would be beneficial to everyone involved in the design and performance evaluation of WHRS with PHE in many industrial sectors. It is clear that employing PHEs operating optimum conditions contribute energy savings, decrease energy cost, improve environmental impacts and shorten process period and supply economical benefits for textile industry as well as the other industrial sectors.

Contents

1. Introduction

Energy saving is a key aim of the world economy and will continue to be one in the future. The most effective way to reduce energy demand is to use energy more efficiently. Heat

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Nomenclature

$\dot{Q}$	heat transfer rate (kW)
$\dot{m}$	mass flow rate (m^3/h)
C_p	fluid specific heat (J/kg K)
C	heat capacity
T	temperature (K)
R	ratio of the minimum and maximum heat capacity rates
NTU	number of heat transfer units
U	overall heat transfer coefficient (W/m^2 K)
A	heat transfer area (m^2)
ΔT_{lm}	Logarithmic temperature difference (K)
$\dot{E}x$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
s	specific entropy (kJ/kg K)
$\dot{S}$	entropy (kJ/kg)
IP	exergetic improvement potential rate (kW)

Greek letters

ε	heat exchanger effectiveness
η_{II}	the second law efficiency
Ψ	flow (specific) exergy (kJ/kg)

Subscripts

max	maximum
ww	waste water
cw	cold water
out	outlet
in	inlet
dest	destructed
min	minimum
mass	mass
°	dead state
gen	generated

exchangers are widely used in power engineering, chemical industries, petroleum refineries, and textile and food industries; in heat engines, cars, tractors, boats, and ships; in aviation and space vehicles; in refrigerant and cryogenic engineering; in space conditioning, heating, and hot water supply systems; and in many other fields of technology. The optimal use of energy and efficient heat transfer becomes of vital importance as a result of the diminishing world energy resources and increasing energy cost [1]. Textile industry plays an important role economically in Turkey. A great amount of hot waste liquids and gases are let out in many textile processes. These waste liquids and gases have crucial energy saving potential, especially for dyeing process. It could be possible to provide energy saving by employing a waste heat recovery system (WHRS). While energy saving could be enhanced by utilizing such a recovery systems, environment protection could be encouraged by releasing waste liquids at lower temperature. There are many advantages of waste heat recovery systems for textile industry: (a) decreasing energy cost, (b) decreasing heat demand, (c) removing time and energy need to heating running water in the beginning of the process, (d) reducing thermal strains for dyeing machines, (e) increasing production volume by shortening the process period, and (f) decreasing overall production cost.

There are numerous studies on waste heat recovery systems in the literature. A counter flow plate heat exchangers (PHEs) for waste heat recovery have been considered in the present study. Yilmaz et al. presented second-law based performance evaluation criteria to evaluate the performance of heat exchangers. They handled entropy and exergy as evaluation parameters [1]. R.T. Ogulata et al. studied and manufactured a counter flow plate heat exchanger which utilizes air as working fluids in laboratory conditions. They analysed the system with respect to the second law of thermodynamics in the cross flow heat exchanger [2]. Ogulata discussed the waste heat recovery potential by a recuperator for drying application in textile industry [3]. Naphon presented the theoretical and experimental results of the second law analysis on the heat transfer and flow of a horizontal concentric tube heat exchanger. It was discussed the effects of the inlet conditions of both working fluids flowing through the heat exchanger on the heat transfer characteristics, entropy generation, and exergy loss [4]. San et al. and San and Pai dealt with the heat transfer performance of a cross-flow serpentine heat exchanger for waste heat recovery and performed a second-law analysis in their studies. Their results showed that increasing the number of passes of the heat exchanger can largely increase the exergetic efficiency [5,6]. Tadini et al. presented a parameter estimation procedure for plate heat exchangers that handles experimental data from multiple configurations. They tested the procedure with a heat exchanger with flat plates and compared the parameter estimation results obtained from the usual method of single-pass arrangements. They pointed that the heat transfer correlations obtained for plate heat exchangers were intimately associated with the configurations experimentally tested and the corresponding flow distribution patterns [7]. Can et al. investigated the potential of waste-heat obtained from particularly dyeing process at textile industry in Bursa, Turkey. A thermodynamic analysis was performed in this parametrical study. The variations of the parameters which affect the system performance such as waste-water inlet temperature, mass flow rate, cooling water inlet pressure and dead state conditions were examined, respectively. They show that the exergy destruction rate and economical profit increase with increasing of mass flow rate of the waste water. It was found that exergy destruction rate, effectiveness and economical profit increase while the second law efficiency decreases as the waste-water inlet temperature increases [8].

In the present study, it is aimed to evaluate optimum operation condition of waste heat recovery system (WHRS) employing a plate heat exchanger (PHE) for textile industry. The WHRS has been established of a well-known blanket manufactory located in Usak Organized Industrial Zone (UOIZ), Turkey has been evaluated. The hot waste liquids from the dyeing process have been utilized to heat cold water by wide interval PHE. The objectives of the study are to perform thermodynamic analyses by applying the first and second laws, to determine optimum operation condition and to present exergetic improvement potential of the WHRS.

There are countless studies presenting the effect of configuration of PHE on energy performance by NTU method and employing the first law of thermodynamics to determine optimum operation condition. No studies on determination optimum operation conditions by integrating the first and the second law of thermodynamic of WHRS for textile industry have appeared in the open literature to the best of the authors' knowledge. This was the motivation behind the present study. In this regard, the main objectives in doing the present study are as follows: (i) to present a thermodynamical model for energy and exergy analysis of the PHE systems, (ii) to apply the model to the system for waste heat recovery for textile industry, (iii) to discuss the parameters affecting system performance, (iv) to determine optimum mass flow rate for waste water and cold water of PHE, and (v) to present exergetic improvement potential and make new suggestions to increase energy and exergy efficiencies of the system.

The originality of the system employed for the present study can be listed as follows: (i) to overcome the negative effect of textile husks in the waste water on the performance of PHE, (ii) to choose a PHE which is wide interval and counter flow arrangement,

(iii) to design a special filter system, (iv) to have an ability to compare the performance of dyeing process with and without WHRS, and (v) to present a new approach by integrating the first and the second law of thermodynamics to determine optimum operation condition. The present study has a great potential to serve applications of WHRS for textile application especially dyeing process as well as the other sectors which are employing heat exchangers in their processes. It is expected that the approach presented here would be beneficial to everyone involved in the design and performance evaluation of WHRS with PHE in many industrial sectors. It is clear that employing PHEs opening optimum conditions contribute energy savings, decrease energy cost and shorten process period and supply economical benefits for textile industry as well as the other industrial sectors. The scope of the present study has been limited by the application of WHRS via counter flow PHE for dyeing process in a textile industry.

The paper is organized as follows: Section 1 includes a brief review, comprehending usage and energy analysis of PHE system as well as exergy analysis of WHRS. The objectives and the originality of the present study are also emphasized in this section. The theoretical model for energy and exergy analysis is given in Section 2. The system description, experimental setup and the data used in the calculations and the results of the model application are covered in Section 3, while the last section gets conclusions. Although the economical analysis of the PHE system for textile industry has been carried out and achieved very sufficient results, it was not involved for the scope of the present study.

2. Thermodynamic analysis

It is very important to perform thermodynamic analysis including the first and the second law for the heat exchangers to calculate heat transfer rate, to determine the effects of mass flow rate and temperatures on the system efficiency and to present optimum operating conditions. In this section, theoretical equations are presented to determine thermodynamic performance of the counter-flow PHE in the experimental system. The following assumptions are considered for the first and second law analyses:

a. All processes are steady state and steady flow with negligible potential and kinetic energy effects and no chemical reaction.
b. There is no heat transfer from the PHE to the environment.
c. The dead state conditions are taken as $T_0 = 20\,^{\circ}\mathrm{C}$
d. There is no temperature difference along the cross-section of the PHE.
e. The heat resistance of the plates is constant along the PHE.
f. There is no phase change in PHE.
g. There is no parallel heat transfer to flow along the liquids or plates.
h. The waste heat liquid is assumed as water.

2.1. The first law analysis

The heat transfer rate for PHE, $\dot{Q}$ is given as follows [7,9,10];

$$\dot{Q} = \dot{m}_{ww} C_{p_{ww}} (T_{ww,in} - T_{ww,out}) \tag{1}$$

where $\dot{m}_{cw}$ is mass flow rate for waste water, $C_{p_{ww}}$ is specific heat for waste water, $T_{ww,in}$ and $T_{ww,out}$ are the inlet and outlet temperatures for waste water, respectively.

According to the first law of thermodynamic, $\dot{Q}$ can be also given as follows [7,9,10]:

$$\dot{Q} = \dot{m}_{cw} C_{p_{cw}} (T_{cw,out} - T_{cw,in}) \tag{2}$$

where $\dot{m}_{cw}$ is mass flow rate of cold water, $C_{p_{cw}}$ is specific heat for cold water, $T_{cw,in}$ and $T_{cw,out}$ are the inlet and outlet temperatures for cold water, respectively.

The heat exchanger effectiveness, ε, is an important parameter for design studies and it is defined as the ratio of the actual rate ($\dot{Q}$) of heat transfer in a given heat exchanger to the maximum possible rate of heat exchange $\dot{Q}_{\max}$. The ε-NTU method is well accepted method in the literature and the effectiveness can be given by [8,9]:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} \tag{3}$$

$\dot{Q}_{\max}$ is calculated from

$$\dot{Q}_{\max} = C_{\min}(T_{ww,in} - T_{cw,in}) \tag{4}$$

where $C_{\min}$ is smaller of the heat capacities for waste (C_{ww}) and cold water (C_{cw}) [11,12].

C_{ww} and C_{cw} are calculated by following relations:

$$C_{ww} = \dot{m}_{ww} C_{p_{ww}} \tag{5}$$

$$C_{cw} = \dot{m}_{cw} C_{p_{cw}} \tag{6}$$

$C_{\max}$ is larger of the heat capacities for waste (C_{ww}) and cold water (C_{cw}) [11,12].

NTU or the number of heat transfer units is defined by [13]

$$\mathrm{NTU} = \frac{UA}{C_{\min}} \tag{7}$$

where U is the overall heat transfer coefficient and A is heat transfer surface area. The NTU is a measure of the heat transfer surface area requirements for a heat demand or the size of the exchanger. NTU is the ratio of the minimum and maximum heat capacity rates of the two fluid streams by [13]

$$R = \frac{C_{\min}}{C_{\max}} \tag{8}$$

The effectiveness of a counter-flow heat exchanger can be calculated as following equation [12,13]:

$$\varepsilon = \frac{1 - \exp[-1(1-R)\mathrm{NTU}]}{1 - R \cdot \exp[-(1-R)\mathrm{NTU}]} \tag{9}$$

The overall heat transfer coefficient U can be found by following relation

$$U = \frac{\dot{Q}}{A \Delta T_{lm}} \tag{10}$$

where ΔT_{lm} is logarithmic mean temperature difference.

ΔT_{lm} is calculated for a counter-flow arrangement as follows [12,13]:

$$\Delta T_{lm} = \frac{(T_{ww,in} - T_{cw,out}) - (T_{ww,out} - T_{cw,in})}{\ln((T_{ww,in} - T_{cw,out})/(T_{ww,out} - T_{cw,in}))} \tag{11}$$

2.2. The second law analysis

The first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be created or destroyed. The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems. It is concerned with the degradation of energy during a process and the entropy generation. It is very helpful to perform exergy analysis to determine optimum operation conditions for a thermal system [14,15].

The exergy balance relation above can be stated as the rate of exergy change within the control volume during a process is equal to the rate of net exergy transfer through the control volume boundary by heat, work, and mass flow minus the rate of exergy destruction within the boundaries of the control volume. Exergy

balance for any system undergoing any process can be expressed as;

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \sum \dot{E}x_{desc} = \Delta\dot{E}_x \quad (12)$$

where $\dot{E}x_{desc}$ is exergy destruction rate, $\dot{E}x_{in}$ is input exergy rate, $\dot{E}x_{out}$ is output rate and $\Delta\dot{E}_x$ is rate of exergy change [14,15].

Most control volumes encountered in practice such as turbines, compressors, nozzles, diffusers, heat exchangers, pipes, and ducts operate steadily, and thus they experience no changes in their mass, energy, entropy, and exergy contents as well as their volumes. The amount of exergy entering a steady flow system in all forms (heat, work, mass transfer) must be equal to the amount of exergy leaving plus the exergy destroyed. Then the rate form of the general exergy balance is defined as follows [14,15]:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{desc} \quad (13)$$

Inlet exergy rate by mass transfer, $\dot{E}x_{mass,in}$, for a heat exchanger can be presented by following equations:

$$\sum x_{mass,in} = \sum \dot{m}_{in} \times \psi_{in} \quad (14)$$

$$\sum x_{mass,in} = \sum \dot{m}_{ww_{in}} \times \psi_{ww_{in}} + \dot{m}_{cw_{in}} \times \psi_{cw_{in}} \quad (15)$$

Similarly the outlet exergy rate $\dot{E}x_{mass,out}$ can be expressed as follows [15]:

$$\sum x_{mass,out} = \sum \dot{m}_{out} \times \psi_{out} \quad (16)$$

$$\sum x_{mass,out} = \dot{m}_{ww_{out}} \times \psi_{ww_{out}} + \dot{m}_{cw_{out}} \times \psi_{cw_{out}} \quad (17)$$

where $\sum \dot{m}_{out}$ is total outlet mass flow rate, ψ_{out} is outlet specific (flow) exergy, $\psi_{ww_{out}}$ and $\psi_{cw_{out}}$ are specific exergy given above for outlet waste and cold water, respectively.

Inlet and outlet specific (flow) exergies can be calculated as following equations [15]:

$$\psi_{ww_{in}} = (h_{ww_{in}} - h_0) - T_0(s_{ww_{in}} - s_0) \quad (18)$$

$$\psi_{cw_{in}} = (h_{cw_{in}} - h_0) - T_0(s_{cw_{in}} - s_0) \quad (19)$$

$$\psi_{ww_{out}} = (h_{ww_{out}} - h_0) - T_0(s_{ww_{out}} - s_0) \quad (20)$$

$$\psi_{cw_{out}} = (h_{cw_{out}} - h_0) - T_0(s_{cw_{out}} - s_0) \quad (21)$$

where h is enthalpy, s is entropy, and the subscript zero indicates properties at the restricted dead state of is dead state temperature T_0.

The relationship entropy generation $\dot{S}_{gen}$ and dead state temperature can be given as below [14]:

$$\dot{S}_{gen} = \frac{\dot{E}x_{desc}}{T_0} \quad (22)$$

For an adiabatic heat exchanger with two unmixed fluid streams the exergy supplied is the decrease in the exergy of the hot stream, and the exergy recovered is the increase in the exergy of the cold stream, provided that the cold stream is not at a lower temperature than the surroundings. Then the second-law efficiency η_{II} of the heat exchanger can be defined as follows [14]:

$$\eta_{II} = \frac{\dot{m}_{cw}(\psi_{cw_{out}} - \psi_{cw_{in}})}{\dot{m}_{ww}(\psi_{ww_{in}} - \psi_{ww_{out}})} \quad (23)$$

Maximum improvement in the exergy efficiency for a process or system is obviously achieved when the exergy loss or irreversibility is minimized [14]. The concept of exergetic improvement potential could be considered as beneficial to determine optimum operation conditions and analyse the system economically. Exergetic improvement potential $I\dot{P}$ can be presented as below [14]:

$$I\dot{P} = (1 - \eta_{II})\dot{E}x_{desc} \quad (24)$$

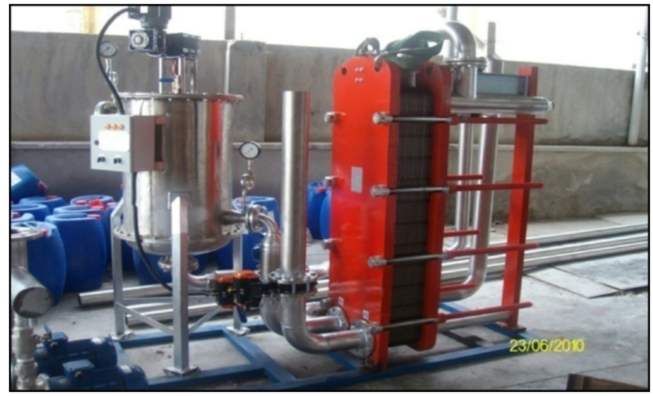


Fig. 1. The counter-flow PHE employing in experimental setup.

3. Results and discussion

The counter-flow heat exchanger has been established in a dyeing plant which processes cotton and acrylic fibers of a well-known blanket manufactory in Usak Organized Industrial Zone (UOIZ), Turkey. The manufactory is one of the best producers that fabricates 5000 blankets in a day and exports most of their outcomes. The waste heat recovery system (WHRS) includes an underground reservoir storing hot waste liquids, an automatic filter, a waste water pump, a counter-flow plate heat exchanger and an underground storage for clean hot water. Fig. 1 shows that the counter-flow plate heat exchanger employing in the experiments. The basic properties of the PHE employing in the system are presented in Table 1.

A Pt-100 resistance thermometer, Enda ETTC 4420 temperature display (±0.2%) and LZ series plastical tube debimeter (±4%) were used to gain temperature and mass flow rate data in the experiments. Fifteen data was measured for each mass flow rate value and their arithmetical average values have been employed for the analyses. The data has been collected for steady-state operation conditions.

In this section, thermodynamic analysis of the PHE system to determine the optimum operation condition was performed by the experimental data. First of all, the relationship between effectiveness of the PHE and number of transfer unit was presented. The variation of heat transfer ratio with waste water mass flow rate for different cold water mass flow rates was shown to realize the first law analysis. Relating to the second law, variations of exergy destruction and exergy efficiency with waste water flow rates for different cold water flow rates were examined. Similarly variations of exergy efficiency and effectiveness with waste water flow rates for different cold water flow rates were evaluated. The optimum waste water flow rate was determined by

Table 1
The basic properties of the PHE employing for the experiments.

Total heat transfer area	20.02 m^2
Plate number	37
Plate thickness	0.9 mm
Plate material	AISI 316
Compressed plate thickness	222 mm
Maximum operating pressure	10 bar
Gasket material	Nitryl
Heat capacity	323 kW

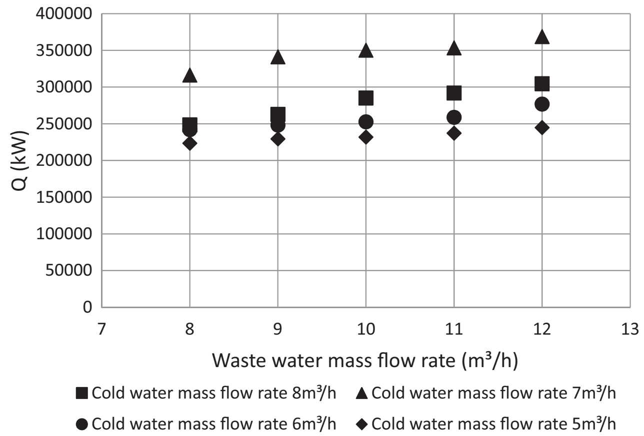


Fig. 2. The heat transfer ratio by waste water mass flow rates at different cold water mass flow rates.

these results. Then by exergy destruction–exergy efficiency and exergy efficiency–effectiveness were investigated by different cold water mass flow rates at the optimum waste water flow rate to define optimum cold water mass flow rate. Hereby optimum waste and cold water mass flow rates were achieved. Exergy destruction–exergy efficiency and exergy efficiency–effectiveness relationships were examined by different waste water inlet temperatures at optimum flow rates. Finally, exergetic improvement potential was evaluated by waste water mass flow rates at different cold water mass flow rates to develop the system thermodynamically.

The heat transfer ratio by waste water mass flow rates at different cold water mass flow rates is presented in Fig. 2. The heat transfer ratio increases by increasing waste water mass flow rates at constant cold water mass flow rate. Maximum heat transfer rate was observed at the value 7 m^3/h of cold water flow rate.

Plots of the effectiveness of PHE versus the number of transfer units are shown in Fig. 3. The effectiveness varies by NTU exponentially as expected.

The variations of exergy destruction rate and exergy efficiency with waste water mass flow rate at constant cold water mass flow rate values which are 8 m^3/h, 7 m^3/h, 6 m^3/h and 5 m^3/h, respectively are represented in left side of Fig. 4. Similarly variations of effectiveness of PHE and exergy efficiency with waste water mass flow rate at the same cold water mass flow rate values were shown in right side of this figure. In the study, the waste water mass flow rate values were changed between 8 and 12 m^3/h at constant cold water mass flow rate values of 5, 6, 7 and 8 m^3/h, respectively, then the inlet and outlet temperatures of PHE were recorded. The left side of Fig. 4 indicates that the exergy destruction rates increases

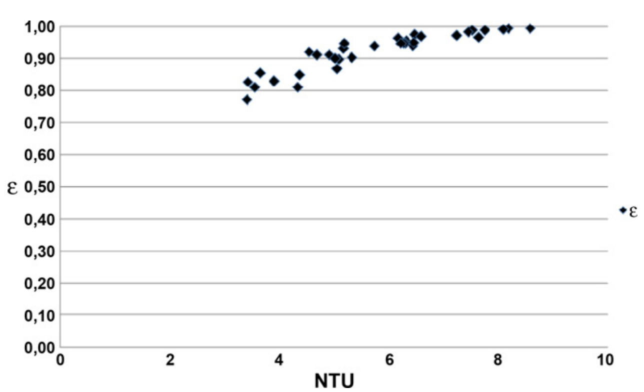


Fig. 3. The variation of PHE effectiveness by the number of transfer units (NTU).

by increasing waste water mass flow rate values at a constant cold water mass flow rate while the exergy efficiency decreases for the same operating conditions. While the waste water mass flow rate varies between 8 and 12 m^3/h, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 5.55 to 13.68 kW; from 53.6% to 67.2% and from 0.996 to 0.810, respectively.

It could be interpreted that the effectiveness of the PHE represents the first law efficiency of thermodynamic. In addition, exergy efficiency is an important marker to evaluate the availability of a system by the second law of thermodynamic. Both of the effectiveness and exergy efficiency are desired to have high values for a PHE. However, while the effectiveness increases by increasing waste water mass flow rate, the exergy efficiency decreases by increasing waste water mass flow rate at a constant cold water mass flow rate. This new approach integrating the first and second law analysis presents an important result: the interception point of the exergy efficiency and effectiveness graphics gives the optimum waste water mass flow rate of the PHE. These optimum waste water mass flow rate values were found 10.31; 9.96; 10.32; 10.08 m^3/h for cold water mass flow rate values of 8, 7, 6 and 5 m^3/h, respectively. The aim of this approach is to determine optimum flow rates. The average value of these optimum mass flow rates is found as 10.17 m^3/h. This optimum waste water mass flow rate is assumed as 10.00 m^3/h to provide convenience in practice.

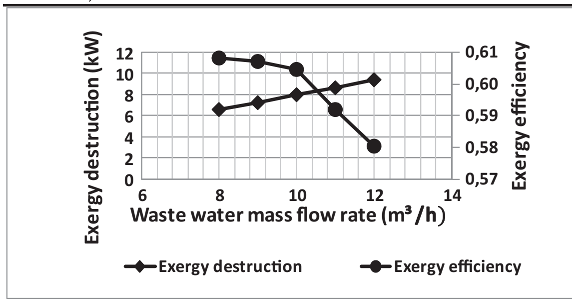
After the optimum waste water mass flow rate was determined, the optimum cold water mass flow rate was investigated. The variations of exergy destruction rate and exergy efficiency with cold water mass flow (left side) and variations of effectiveness of PHE and exergy efficiency with cold water mass flow rate (right side) at optimum waste water mass flow rate are shown in Fig. 5. While the cold water mass flow rate varies between 5 and 9 m^3/h, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 8.05 to 10.89 kW; from %56.3% to %63.9% and from 0.868 to 0.991, respectively. From Fig. 5, the interception point of the exergy efficiency and effectiveness graphics gives the optimum cold water mass flow rate of the PHE. This optimum water mass flow rate value was found 6.46 m^3/h on right graph. On the other hand, while the exergy destruction has minimum value at cold water mass flow rate of 7.00 m^3/h, the exergy efficiency has a maximum point.

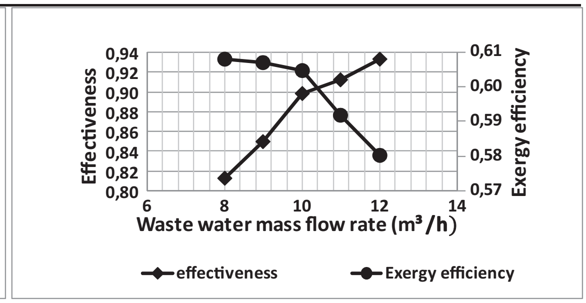
This cold water mass flow rate value was determined as an optimum point. In the same way as waste water mass flow rate, the optimum cold water mass flow rate was chosen as 7.00 m^3/h for practical application.

The optimum waste and cold water mass flow rates were fixed at 10.00 m^3/h and 7.00 m^3/h, respectively. Then the effect of waste water inlet temperature on the system performance was examined. The variations of exergy destruction rate and exergy efficiency with waste water inlet temperature (left side) and variations of effectiveness of PHE and exergy efficiency with waste water inlet temperature (right side) are presented in Fig. 6. Exergy destruction rate increases as exergy efficiency decreases with increasing waste water inlet temperature. While the waste water inlet temperatures varies between 52.4 and 59.5 °C, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 5.40 to 9.46 kW; from 68.7% to 61.6% and from 0.969 to 0.924, respectively. It is seen that both of effectiveness and exergy efficiency decrease by increasing waste water inlet temperature values on the right side of Fig. 6. The reason of this case could be explained as follows: logarithmic temperature difference increases by higher waste water inlet temperature values. Correspondingly, overall heat transfer coefficient decreases; NTU and effectiveness decrease consequently.

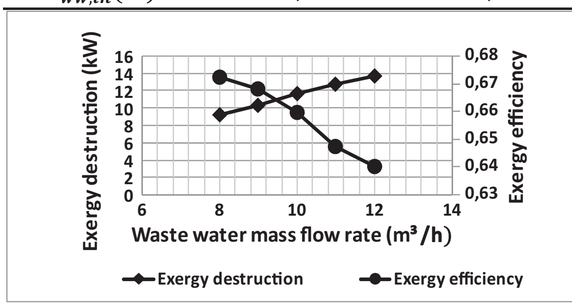
The variation of exergetic improvement potential rate with waste water mass flow rate at a constant cold water mass flow

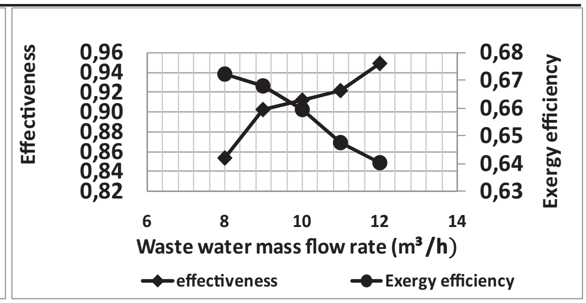
$\dot{m}_{cw} = 8\ m^3/h$			$T_{cw,in} = 23,5\,°C$		
$\dot{m}_{ww}(m^3/h)$	8	9	10	11	12
$T_{ww,in}(°C)$	54,7	54,6	54,5	54,3	54,2



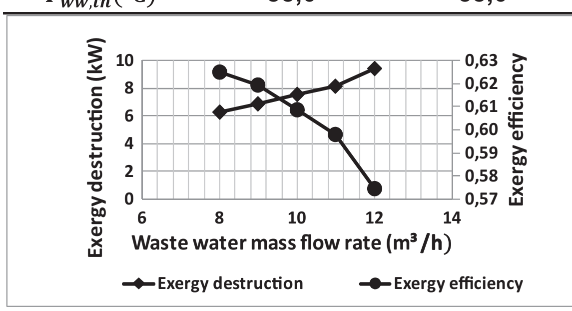


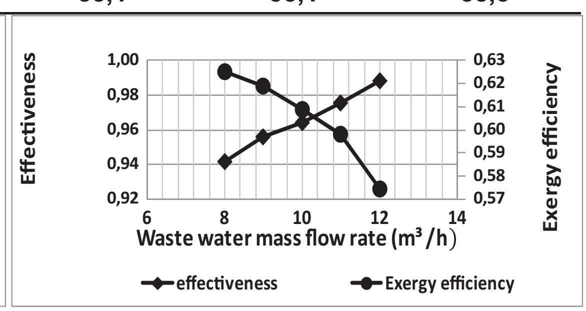
$\dot{m}_{cw} = 7\ m^3/h$			$T_{cw,in} = 21,1\,°C$		
$\dot{m}_{ww}(m^3/h)$	8	9	10	11	12
$T_{ww,in}(°C)$	65,8	65,9	67	67,1	66,9



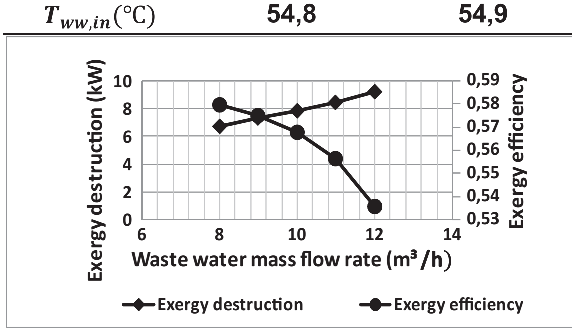


$\dot{m}_{cw} = 6\ m^3/h$			$T_{cw,in} = 22,1\,°C$		
$\dot{m}_{ww}(m^3/h)$	8	9	10	11	12
$T_{ww,in}(°C)$	55,0	55,0	55,1	55,1	55,3





$\dot{m}_{cw} = 5\ m^3/h$			$T_{cw,in} = 22,1\,°C$		
$\dot{m}_{ww}(m^3/h)$	8	9	10	11	12
$T_{ww,in}(°C)$	54,8	54,9	54,9	55,0	55,0



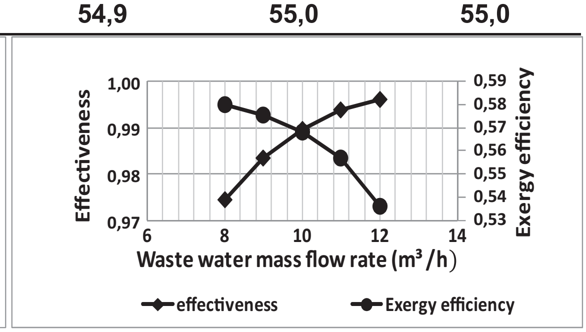


Fig. 4. The variations of exergy destruction rate and exergy efficiency with waste water mass flow (left side) and variations of effectiveness of PHE and exergy efficiency with waste water mass flow rate (right side).

$\dot{m}_{ww} = 10\ m^3/h$			$T_{cw,in} = 24,1$°C		
$\dot{m}_{cw}(m^3/h)$	5	6	7	8	9
$T_{ww,in}$(°C)	57,1	57,2	57,4	58,2	58,0

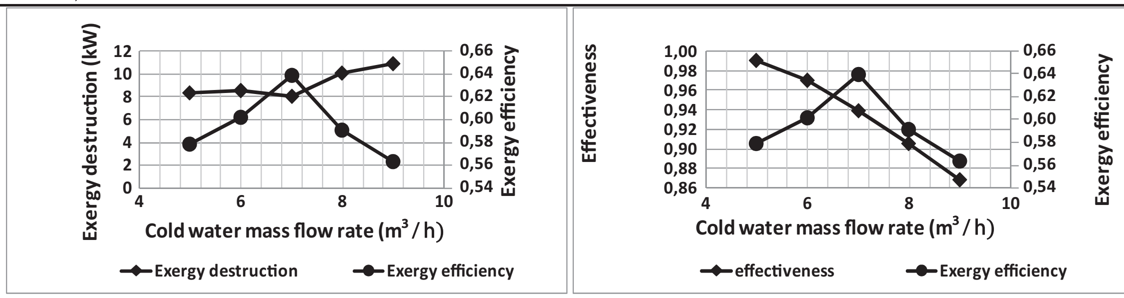


Fig. 5. The variations of exergy destruction rate and exergy efficiency with cold water mass flow (left side) and variations of effectiveness of PHE and exergy efficiency with cold water mass flow rate (right side).

$\dot{m}_{ww} = 10\ m^3/h$			$\dot{m}_{cw} = 7\ m^3/h$		$T_{cw,in} = 23,9$°C		
$T_{ww,in}$(°C)	52,4	53,7	54,1	55,1	55,5	57,4	59,5

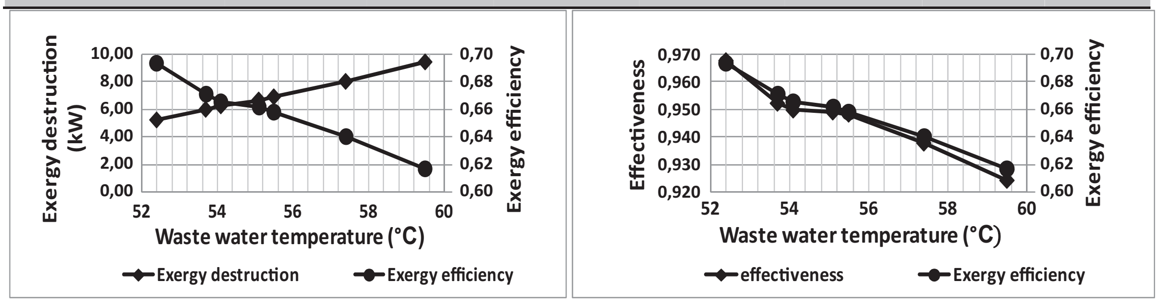


Fig. 6. The variations of exergy destruction rate and exergy efficiency with waste water inlet temperature (left side) and variations of effectiveness of PHE and exergy efficiency with waste water inlet temperature (right side).

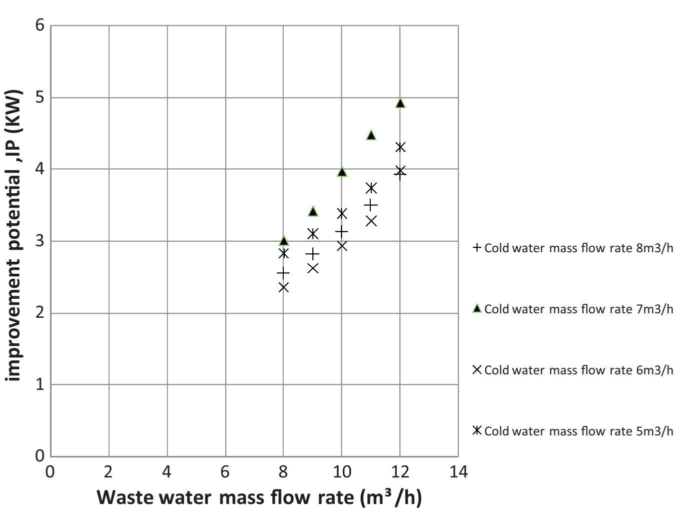


Fig. 7. The variation of improvement potential with waste water mass flow rate.

rate is shown in Fig. 7. Exergetic improvement potential rises by increasing waste water mass flow rate.

4. Conclusion

The optimum operation conditions were assessed by integrating the first and the second law of thermodynamics for a counter flow PHE employed for a dyeing process in textile industry. The main conclusions, which may be drawn from the results of the present study, are listed as follows:

a. The heat transfer ratio increases by increasing waste water mass flow rates at constant cold water mass flow rate.
b. While the effectiveness of PHE varies between 0.773 and 0.996, NTU has the values from 3.41 to 8.60.
c. The exergy destruction rate increases by increasing waste water mass flow rate values at a constant cold water mass flow rate while the exergy efficiency decreases for the same operating conditions. While the waste water mass flow rate varies between 8 and 12 m^3/h, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 5.55 to 13.68 kW; from 53.6% to 67.2% and from 0.996 to 0.810, respectively.
d. Optimum waste water mass flow rate values were found 10.31; 9.96; 10.32; 10.08 m^3/h for cold water mass flow rate values of 8, 7, 6 and 5 m^3/h, respectively. Optimum waste water mass flow rate is assumed as 10.00 m^3/h to provide facility in practice.
e. While the cold water mass flow rate varies between 5 and 9 m^3/h, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 8.05 to 10.89 kW; from %56.3% to %63.9% and from 0.868 to 0.991, respectively.
f. The optimum cold water mass flow rate was determined as 7.00 m^3/h for practical application.
g. While the waste water inlet temperatures varies between 52.4 and 59.5 °C, exergy destruction rate, exergy efficiency and effectiveness of the PHE have the values from 5.40 to 9.46 kW; from 68.7% to 61.6% and from 0.969 to 0.924, respectively at optimum mass flow rates.

h. While the exergetic improvement potential varies between 2.35 and 4.92 kW, waste and cold water mass flow rates have the values from 8 to 12 m^3/h and from 5 to 8 m^3/h, respectively.

The present study has a great potential to serve applications of WHRS for textile application especially dyeing process. It is expected that the approach presented here would be beneficial to everyone involved in the design and performance evaluation of WHRS with PHE in many industrial sectors. It is clear that employing PHEs operating optimum conditions contribute energy savings, decrease energy cost, improve environmental impacts and shorten process period and supply economical benefits for textile industry as well as the other industrial sectors.

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References

[1] Yilmaz M, Sara ON, Karsli S. Performance evaluation criteria for heat exchangers based on second law analysis. Exergy International Journal 2001;1(4): 278–94.
[2] Ogulata RT, Doba F, Yilmaz T. Second-law and experimental analysis of a cross-flow heat exchanger. Heat Transfer Engineering 1999;20(2):20–7.
[3] Ogulata RT. Utilization of waste-heat recovery in textile drying. Applied Energy 2004;79:41–9.
[4] Naphon P. Second law analysis on the heat transfer of the horizontal concentric tube heat exchanger. International Communications in Heat and Mass Transfer 2006;33:1029–41.
[5] San J-Y, Lin G-S, Pai K-L. Performance of a serpentine heat exchanger: part I – effectiveness and heat transfer characteristics. Applied Thermal Engineering 2009;29:3081–7.
[6] San J-Y, Pai K-L. Performance of a serpentine heat exchanger: part II – second-law efficiency. Applied Thermal Engineering 2009;29:3088–93.
[7] Gut JAW, Fernandes R, Pinto JM, Tadini CC. Thermal model validation of plate heat exchangers with generalized configurations. Chemical Engineering Science 2004;59:4591–600.
[8] Pulat E, Etemoglu AB, Can M. Waste-heat recovery potential in Turkish textile industry: case study for city of Bursa. Renewable and Sustainable Energy Reviews 2009;13:663–72.
[9] Şencan A, Selbaş R, Kılıç B. Isıtma ve soğutma uygulamalarında kullanılan plakalı ısı eşanjörlerinin deneysel analizi. Tübav Bilim Dergisi 2010;3(1):35–44 (in Turkish).
[10] Danışman C, 2010. Plakalı Eşanjör Etkinlik Parametrelerinin Deneysel Analizi, Master Thesis, Eskişehir Osmangazi Üniversitesi, Fen Bilimleri Enstitüsü [in Turkish].
[11] Kakaç S, Liu H. Heat exchangers selection rating and thermal design. New York: CRC Press; 1998. p. 373–412.
[12] Genceli OF. Isı değiştiricileri. İstanbul: Birsen Yayınevi; 2005. p. 90–109, in Turkish.
[13] Wang L, Sundén B, Manglik RM. Plate heat exchangers design, applications and performance. Southampten, Boston: Wit Press; 2007.
[14] Çengel YA, Boles A. Mühendislik Yaklaşımıyla Termodinamik. Izmir: Ali Pınarbaşı, Güven Bilimsel; 2008. p. 423–486, in Turkish.
[15] Hepbasli A. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renewable and Sustainable Energy Reviews 2008;12:593–661.